

# Pomeranchuk effect in unstable *Ytterbium* systems

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$YbInCu_4$  and its alloys present discontinuous, first order iso-structural transitions at pressure dependent temperatures  $T_V(P)$ , where a local moment phase coexist with a renormalized Fermi liquid phase. We show that along the coexistence line  $T_V(P)$  the entropy of the large volume renormalized Fermi liquid phase is smaller than that of the higher density, local moment phase. This implies the existence of a Pomeranchuk effect in these Kondo lattice materials in analogy with  $^3He$ . The theoretical possibility of using these systems as cooling machines is discussed.

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The system  $^3He$  presents the unusual feature that along its melting line, where the solid and liquid phases coexist, the entropy of the liquid is smaller than that of the solid<sup>1,2</sup>. This occurs for a range of temperature  $T < T_N = 0.32K$ , where the melting pressure versus temperature curve has a minimum, but for  $T > T_N$ , the temperature of magnetic ordering of the solid. This feature is the basis of the cooling technique known as the Pomeranchuk effect<sup>1</sup> which had an important practical application as a cooling mechanism to reach very low temperatures in this system. It is believed to be a unique property of quantum  $^3He$  and is a direct consequence that in its liquid phase this is a renormalized Fermi liquid, with a linear temperature dependent entropy ( $S_L/Nk_B = 3.0T$ ) while in the solid phase for the temperature range above, it may be seen as a collection of weakly interacting spin-1/2 local moments with<sup>1</sup>  $S_S/Nk_B \approx \ln 2$ . Also for the low temperatures associated with this behavior of  $^3He$ , elastic excitations (the phonons) are quenched and the relevant degrees of freedom are the magnetic ones due the spin-1/2 nuclei.

The Kondo lattice system  $YbInCu_4$  presents isostructural transitions, which for the pure system at ambient pressure ( $P \approx 1$  bar) occurs at a temperature  $T_V = 42K$ <sup>3,4</sup>. This is a discontinuous, first order transition which is accompanied by large changes in transport properties and in magnetic behavior. In Fig. 1 we show the temperature dependent magnetic susceptibility of  $YbInCu_4$  in the range of the isostructural transition. Above  $T_V$ , the susceptibility is of the Curie-Weiss type characteristic of a system of weakly interacting local moments ( $\Theta \approx -7.2 K$ )<sup>4</sup>. Below the transition, the susceptibility is nearly temperature independent, i.e., Pauli like as in a Fermi liquid. The value of  $\chi_0$  indicates a renormalized value consistent with the coefficient of the linear term in the specific heat,  $\gamma = 50$  mJ/molK<sup>24</sup>. This leads us to consider  $YbInCu_4$  in its low temperature phase as a moderate heavy fermion system.

This picture of  $YbInCu_4$  at  $T_V$  as a renormalized Fermi liquid phase coexisting with a local moment phase at a line of first order transitions  $T_V(P)$  brings out a powerful analogy with  $^3He$ .

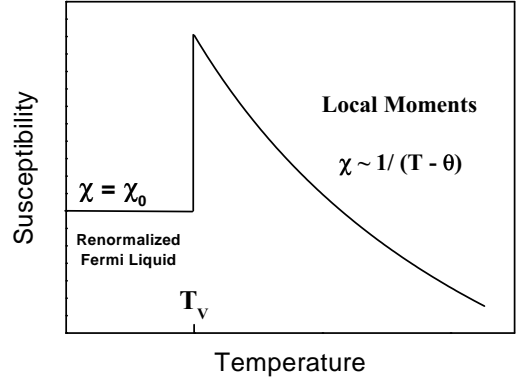


FIG. 1: Susceptibility curve for  $YbInCu_4$  (schematic). At  $T_V \approx 42K$  ( $P = 0$ ) there is a discontinuous, first order iso-structural transition with a volume increase in the low temperature phase. At  $T_V$  a local moment phase coexists with a renormalized Fermi liquid phase<sup>4</sup>.

Along the melting line  $T_m(P)$  of  $^3He$  and the line  $T_V(P)$  of the present system, we find coexistence of a renormalized Fermi liquid phase and a phase of local moments (in  $^3He$  the liquid and solid phases, respectively).

The nature of the coexisting phases in  $YbInCu_4$  leads us to expect that as in  $^3He$ , the Fermi liquid phase of this material has a smaller entropy that of the local moment phase for some range of temperatures where these phases coexist.

The Clausius-Clapeyron equation<sup>2</sup>, as applied to the  $YbInCu_4$  system can be written as,

$$\left(\frac{dP}{dT}\right)_{T_V(P)} = \frac{S_{FL} - S_{LM}}{V_{FL} - V_{LM}} \quad (1)$$

where the derivative is obtained at the volume instability curve  $T_V(P)$ . The entropy of the local moment phase and of the renormalized Fermi liquid phase are given by  $S_{LM}$  and  $S_{FL}$ , respectively. Notice that, since both phases are truly solid and the change in volume is small (see Table I), the difference ( $S_{FL} - S_{LM}$ ) is mostly due to the magnetic degrees of freedom. In  $^3He$  the derivative

in Eq. 1 is calculated at the melting curve where the solid and liquid coexist. In this system, the melting pressure as a function of temperature passes through a minimum at  $T_\times$ , where  $S_{solid} = S_{liquid}$  and presents a negative  $(dP/dT)$  for  $T < T_\times$ , consistent with  $S_{solid} > S_{liquid}$  in this range, since the molar volume of the liquid  $V_L$  is larger than that of the solid,  $V_S$ .<sup>1,2</sup>

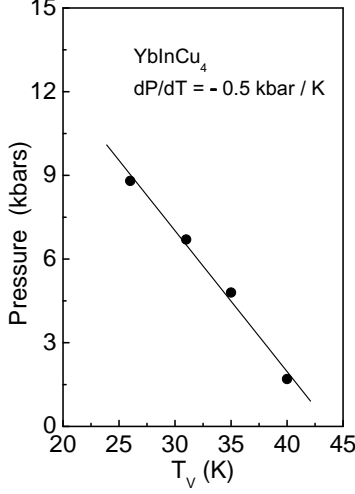


FIG. 2: Pressure of the volume instabilities in  $YbInCu_4$  as a function of temperature, obtained from resistivity measurements<sup>4</sup>.

A plot of the instability temperature for  $YbInCu_4$  as a function of pressure  $T_V(P)$  (or  $P(T_V)$ ), obtained from resistivity measurements<sup>4</sup> is shown in Fig. 2. From the Clausius-Clapeyron equation, the experimental negative sign of  $(dP/dT)$  at  $T_V$  and the fact that the molar volume in the Fermi liquid phase of  $YbInCu_4$  ( $V_{FL}$ ) is larger than that of the local moment phase  $V_{LM}$ , we can conclude that the entropy of the former ( $S_{FL}$ ) at the coexistence line  $P(T_V)$  is smaller than that of the local moment phase, for this range of temperatures, just as in  $^3He$  for  $T < T_\times$ . As pointed out before, the features  $S_{FL} < S_{LM}$ ,  $V_{FL} > V_{LM}$  are at the root of the Pomeranchuk effect in  $^3He$  which, as we have just shown, also occurs in the Kondo lattice system  $YbInCu_4$ .

In Table I we list for comparison some thermodynamic parameters of  $YbInCu_4$  and  $^3He$ . Notice that for the former material,  $(T_\times, P_\times)$  are obtained from a crude extrapolation of the Fermi liquid entropy<sup>4</sup>  $S_{FL}/Nk_B = 6.0 \times 10^{-3}T$  up to that of independent local moments<sup>5</sup>  $S_{LM}/Nk_B = \ln(2J+1) = \ln 8$ .

In the case of  $^3He$  the Pomeranchuk effect is the basis for the construction of a practical apparatus which has provided the means for attaining very low temperatures in this system and eventually discovering its superfluid phases<sup>1</sup>. The results above show the theoretical possibility of constructing a Pomeranchuk cooling machine based on the Kondo lattice system  $YbInCu_4$ . An estimation of the cooling efficiency of such machine is given by the

	$^3He$	$YbInCu_4$
Large Volume Phase ( $V_L$ )	Liquid	Fermi Liquid
Small Volume Phase ( $V_S$ )	Solid	Local Moment
$(V_L - V_S)/V_L$	0.05	0.005
$(dP/dT)(kbar/K)$	- 0.016	- 0.5
$(W/Q)$	> 13	0.08 ( $T = 40K$ )
$(T_\times, P_\times)$ (K, kbar)	(0.32, 0.029)	(346, -151)

TABLE I: Thermodynamic parameters for  $^3He$ , Ref. <sup>2</sup> and  $YbInCu_4$ , Ref. <sup>4</sup>.  $(T_\times, P_\times)$  for  $YbInCu_4$  were obtained extrapolating the Fermi liquid entropy to reach to non-interacting local moment value.

ratio  $(W/Q)$ , where  $W = P_V(V_{FL} - V_{LM})$  is the compressional work to squeeze the Fermi liquid into the local moment phase. The quantity  $Q = T(S_{LM} - S_{FL})$  is the latent heat which represents the maximum amount of heat which can be removed by converting the Fermi liquid into the local moment phase. The ratio  $W/Q = -(P_V/T)(dP_V/dT)^{-1}$  attains for  $^3He$  its lowest value,  $(W/Q) = 13$ , at  $T = 0.14K^2$ . For  $YbInCu_4$  this can be much smaller, for example,  $(W/Q) = 0.08$  at  $T = 40K$  using the value of  $(dP_V/dT)$  obtained from Fig. 2 (see Table I).

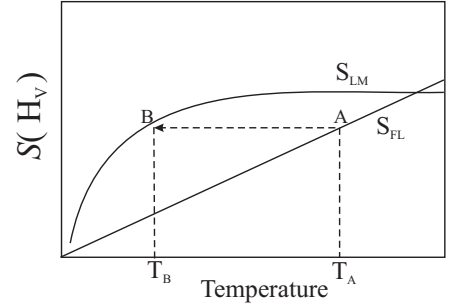


FIG. 3: Schematic temperature variation of the entropy of the Fermi liquid and local moment phases at the instability field  $H_V$ . Cooling can be achieved by isentropically increasing the magnetic field to bring the FL phase into the LM phase as in a process from A to B.

Notice however that instead of adiabatically squeezing  $YbInCu_4$  to transform the Fermi liquid into the local moment phase and reduce the temperature, it is easier to play with the magnetic field<sup>4,5</sup> which strongly affects the volume transition at  $T_V$ . In Fig. 3 we show schematically the temperature dependence of the entropy  $S(H_V, T)$  of the Fermi liquid and local moment phases at the instability field  $H_V$ . A similar curve is obtained for  $S(P_V, T)$ . Cooling can be achieved by isentropically increasing the magnetic field to bring the Fermi liquid into the local moment phase, as in the process  $A \rightarrow B$  illustrated in the figure. We point out that  $T_V(H)$  is a universal decreasing function<sup>4</sup> of  $H_V$ . Then, the magnetic field can

be used as the *compressing agent* which is simpler than actually squeezing the Fermi liquid.

In this Letter we have shown the existence of a Pomeranchuk effect in  $YbInCu_4$  and its alloys, which opens the theoretical possibility of using these materials as cooling machines. Our approach suggests to view the transition at  $T_V$  in  $YbInCu_4$  as the melting of a Kondo lattice.

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<sup>1</sup> I. Pomeranchuk, Zh. Eksp. i Teor. Fiz. (USSR) **20**, 919 (1950); R. C. Richardson, Rev. Mod. Phys. **69**, 683 (1997).

<sup>2</sup> D. S. Betts, *Refrigeration and Thermometry below One Kelvin*, Sussex University Press, 1976.

<sup>3</sup> I. Felner and I. Nowik, Phys. Rev. **B33**, 617 (1986).

<sup>4</sup> J. L. Sarrao, Physica **B259-261**, 128 (1999) and references therein.

<sup>5</sup> M.O. Dzero, L.P. Gorkov and A.K. Zvezdin, J.Phys.-Cond.Mat. **12**, L711 (2000).